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SATELLITE OCEANOGRAPHY OF EASTERN BOUNDARY CURRENTS AND ITS IMP--ETC(U)

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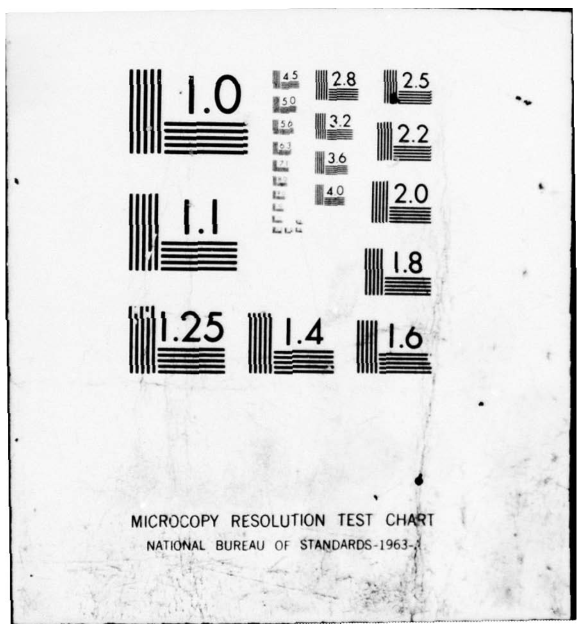
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SATELLITE OCEANOGRAPHY OF EASTERN BOUNDARY CURRENTS AND ITS IMPLICATIONS TO ASW

by

ROBERT E. STEVENSON

1 NOVEMBER 1978

NORTH ATLANTIC TREATY ORGANIZATION

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The opinions expressed herein are those of the authors and are not necessarily the official views of the SACLANT ASW Research Centre.

SATELLITE OCEANOGRAPHY OF EASTERN BOUNDARY CURRENTS AND ITS IMPLICATIONS TO ASW

by

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ABSTRACT

The characteristics of western boundary currents are better known than those along the eastern edges of oceans. Gulf-stream fronts and rings continue to be popular research subjects, as are the more recently discovered ANZUS eddies off Australia. In the 1970s, however, close attention has been given to eastern boundary currents. The variability of the El Nino phenomenon off Peru, and coastal upwelling off Oregon, Peru/Chile, and Northwest Africa, have been studied by multi-national teams. Since 1975, U.S. Navy personnel and scientists sponsored by the Office of Naval Research have examined satellite imagery of the waters off California and Western Europe as a first step in real-time satellite oceanography. From these studies, we know now that eastern boundary currents have identifiable fronts (such as the Huelva front) and eddies (like the Socal eddy chain) that vary seasonally and inter-annually in intensity and scale. The fronts have lengths of tens of kilometres and depths of hundreds of metres; the eddies have diameters of 50 to 200 km and depths greater than 500 m. Both the eddies and fronts have surface temperature gradients of 1.5°C to 5°C. Deeper, the temperature gradients tend to be sharper than those at the surface. Off the west coast of the United States, most of the turbulence in the boundary current is within 300 km of the shore. Topographic influence is significant off Cape Mendocino and Pt. Conception. The width of the turbulent system is not as regular off Western Europe, and major complexities are created in the Bay of Biscay, Gulf of Cadiz, and off Cabo St. Vincente. The thermal gradients and surface texture of the fronts and eddies permit routine surveillance from satellites. The data are useful therefore in solving tactical ASW problems.

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FOREWORD

The paper presented here was originally read at the Conference on "ASW in the Southwestern Approaches to the English Channel", held at SACLANT ASW Research Centre, La Spezia, Italy during the period 14-16 March 1978. The proceedings of that conference were published in April 1978 as SACLANTCEN CP-22, but administrative difficulties prevented the author from meeting the publication deadline. The text and illustrations of the presentation have now been received at SACLANTCEN and are reproduced here as a SACLANTCEN Special Report for distribution to holders of the Conference Proceedings and other interested persons.

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October 1978

Satellite Oceanography of Eastern Boundary Currents
and its Implications to ASW

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To all mariners, the general circulation of the ocean is well known. Moved primarily by the constant equatorial trade winds and the mid-latitude westerlies, the ocean currents flow in predictable paths. They may exhibit seasonal and annual variations, in speed and the temperatures of their waters, but they continue to move in manners that are always measurable.

For many obvious reasons, the Gulf Stream is the most renowned ocean current, and the most studied. Its location and speed was used to advantage by whaling captains in the 18th and 19th century. This practice so impressed Benjamin Franklin, then Postmaster General in America, that he had a chart published for captains sailing aboard mail packets between the New World and England.

As oceanographic studies of the Gulf Stream in the late twentieth century became more sophisticated than in the early 1900's, the supposed simplicity of the current system was seen to be a myth. Old claims by ship captains that they could "set up their position" by the boundary of "The Stream" was a figment of their imaginative navigation.

From the infrared thermal range scanner on NOAA-5, with the simultaneously gathered visual scene, we can easily see the sharp temperature gradients, the major eddies, and the turbulence of the current boundaries that characterize the Gulf Stream (Fig. 1).

The total sea-surface temperature range depicted in this image is 16° C. Because of the gray scales used, the major gradients stand out clearly, and were we to use an appropriate grid, the positions could be plotted with a two nautical mile precision.

In this scene, the temperature boundaries are also visible in the reflection pattern of the sun from the sea surface. The implications of this observation are intriguing because these variations in sea-surface texture are created by differences in ocean temperature.

Complex though the western boundary currents may be, they are surpassed in that regard by the flow of the ocean along its eastern borders. Because the current speeds and width of ocean affected are lesser than in the western oceans, eastern boundary currents are influenced greatly by winds, atmospheric storms, and the coastal topography. The great upwelling areas of the ocean are along its western edges, as are the periodic reversals of upwelling; such as warm El Niño off the coast of Peru.

Though for decades oceanographers have studied eastern boundary currents, especially upwelling waters, the complex eddies, fronts and turbulent sequences were virtually unknown (but speculated on) before the availability of satellite infrared imagery. Because the temperature gradient of these turbulent features have magnitudes of 1° - 5°; whereas those in the west are 5° - 18° C, even rational satellite evaluation had to await the computerized capability of the U. S. Navy's Defense Meteorological Satellite Project (DMSP).

Turbulence similar to that off Lisbon was imaged on 6 September 1977 as the first DMSP in the new Block 5-D satellite series orbited over the western United States on a descending pass. (Fig. 3). In this printout, the lands of Oregon and Washington show as white because they were colder than the coldest water temperature. Coastal

California, on the other hand, was warmer than the warmest water. The computer program blacked out the clouds and rimmed them in white.

The classic Oregon upwelling waters were turbulent that day, with one large, cold-core eddy extending seaward. Off Cape Blanco, an eddy trapped coastal warm water. At Cape Mendocino, sea floor topography; a ridge jutting to the west, creates a seaward flowing jet of cold water extending some 200 miles from shore. This massive eddy, studied by Dr. Robert Bernstein and Robert Whritner, Scripps Institution of Oceanography (SIO), is clear evidence that the California Current rides on top of the sea floor and responds, therefore, to major irregularities in bottom topography.

The most important requirement in establishing rational oceanographic analyses from satellite imagery is to determine the depth relationship between the imaged surface feature and the underlying ocean. A most useful experiment, in this regard, was conducted on 13 and 14 March 1976, by personnel from the U. S. Navy Weather Service Facility (NWSF), North Island, Naval Oceanographic Office, and SIO.

Using a print of an image obtained at the NWSF Satellite Van at 0730, 13 March (Fig. 4), some 30 minutes later, Robert Whritner was aboard a Navoceano RP-3 aiding the crew in the deployment of air expendable bathythermographs (AXBT's). He noted the California Current moving past Pt. Conception in two large cold-water tongues, with cold water refracting around the Point into Santa Barbara Channel. The AXBT's were dropped to verify these apparent temperature gradients.

The next day, Dr. Bernstein, again with the 0730 image in hand, provided a similar service to the Navoceano crew. In all, 88 AXBT's were deployed on the two days.

The surface temperatures from those probes indicated that the evaluation by Whritner and Bernstein was correct (Fig. 5). The heavy black lines mark the boundaries from the satellite image. The cold-warm-cold-warm sequence follows those fronts precisely.

At depth, the gradients were more pronounced than at the surface. At 400 feet, temperature gradients of 3^{o} C bounded the major-cold-warm water tongues (Fig 6). Even more impressive though, was the revelation that the "tongues", both warm and cold, were actually large warm and cold core eddies.

We now know those eddies (the SoCal Eddy Chain) to be quasi-permanent features off southern California, varying with the season and moving slowly as new eddies form behind them.

This information has modified entirely ASW tactics as practiced off southern California.

Off Spain, in the Gulf of Cadiz, an ambitious experiment was conducted during the Apollo/Soyuz Test Project, July 1975.

I have reported on this experiment in considerable detail (Stevenson, 1977), so I'll mention only highlights here.

The ocean off western Spain is somewhat similar to that off southern California in that the main current flows by a headland (Pt. Conception and Cabo Ste. Vicente), and the coastline then falls away from the current as a large bight (the SoCal Bight and the Gulf of Cadiz). Differences are created by the basin-ridge sea floor off southern California *versus* the simple shelf-slope sea floor off Spain.

Both bights have cold water entering from around the major headland, but off Spain that water extends well into the Gulf; the shelf-break apparently acting as a guide. Thus, the formation of the Huelva Front. This tongue of cold water provides the boundary necessary to

trap warm water in the approaches to Gibralter. The resulting eddy is bounded, therefore, by upwelling off Morocco, the cold offshore current, and the Huelva Front.

Good data to verify the front and eddy were obtained on 19, 20 and 21 July 1975 from AXBT's deployed by the U. S. Navy P-3 detachment in the Azores.

The temperature profiles from these air-dropped probes indicate the rising thermocline at the frontal edge, the immediately adjacent warm trough, the shallow, broad "bathtub" of warm water, and the offshore turbulent discontinuity at the boundary of the main current (Fig. 7).

The now-famous image of DMSP infrared data taken aboard the USS Kennedy on 20 July 1975 (Fig. 8) depicts well the cold upwelling waters off Portugal and the cold tongue of the Huelva Front.

Ten days of such data, all from the "Kennedy Tapes" and reduced by personnel at NWSF North Island, permitted a most detailed surface temperature chart to be drawn. The cold tongue from Portugal is squeezed between two warm troughs, the one next to the coast being of lesser salinity than that offshore, no doubt, bringing about even more interesting acoustic implications than merely the front itself (Fig. 9).

From all of the available data, one can then draw a chart of the currents that bounded the fronts and eddy in July 1975 (Fig. 10).

As this was a prime observation site from Apollo, and Major General Thomas Stafford observed clearly and photographed the features in the Gulf of Cadiz, we named the shear-like boundary between the Tarif Eddy and the refracting upwelling waters in his honor.

All of this information was sufficient for the captain and staff of the USS Enterprise to carry out the first tactical ASW maneuver based on satellite oceanography. On 23 June 1976, during Fleet Exercise Readiex 476, the Enterprise was faced with a problem which required the ship to launch aircraft off Santa Barbara after first avoiding an "enemy" submarine force located in warm waters west of Los Angeles.

On the afternoon of the 23rd, the image shown on the left in Figure 11 was flown to the carrier from North Island. Noting that the submarine force lay in the warm, nearshore waters, a plan was made to send the cruiser escorts on a high-speed run to the northwest, drawing, hopefully, the submarines across the cold-water front. The Enterprise was then to proceed quietly northward, staying on the warm side of the front. The maneuver, carried out on the 24th as noted on the drawing, was completely successful.

But, sea stories always carry with them an element of danger and this one was no different. The application of thermal boundaries to ASW is fraught with hazards without a clear understanding of the variations in acoustic propagation, attenuation, or refraction created by the boundary.

Even though such a statement seems patently obvious, the fact is that we know little of the effects of thermal boundaries on underwater acoustics. This is most particularly the case when dealing with those resulting from the complex turbulence in eastern boundary currents.

One of the few experiments conducted to date that is significant to our discussion was ANZUS Eddy, March 1975, in the East Australian Current. The experiment was designed to examine the acoustic properties of a large-warm-core eddy. Led by Paul Scully-Power, then at the Royal Australian Navy Research Laboratory, the effort involved ships from the Australian and New Zealand navies, personnel and

acoustic gear from the Naval Underwater Systems Center, New London, and funds from the Office of Naval Research (Scully-Power, 1977).

The isotherms at 240 m. in the eddy that was studied (Fig. 12) show the eddy to be "open" to the north, a condition quite different from eddies formed during the winter in these waters; the latter being completely closed.

Even so, this eddy exhibited a strong surface sound duct to a depth of about 30 m. and a good eddy duct between 200 and 400 m.

All of the acoustic results satisfied the predicted model. As indicated here, there was a sharp cut-off at all frequencies at the boundary of the eddy (Fig. 13). Some "leakage" was evident, as expected, as well as a strong surface-layer reception, from other data gathered in the surface and eddy duct.

This impressive experiment pointed out the clear necessity for tactical forces to know daily the details of mesoscale ocean in which they plan to operate.

The problem of the "daily mesoscale ocean" can be partly satisfied by the view from space, in both the infrared, as we've seen, and in the visual. This view from Skylab, also illustrates another "evil" of the sea, so typical of eastern boundary currents; the cold-core eddy (Fig. 14).

The first clear recognition of cold-core eddy chains in the ocean came from data gathered aboard the earth-orbiting Skylab. From a series of vertical, stereo photographs taken as the spacecraft was in a descending orbit across the Gulf of Mexico and the Caribbean Sea, cold, cyclonic whirls were noted along the entire western boundary of the current.

In January 1974, while Skylab once again orbited over the Caribbean Sea, a U. S. Navy P-3, from a weather squadron in Jacksonville, Florida, flew a track beneath the spacecraft. Dropping

XBT's every ten nautical miles, while the astronauts above photographed the scene, the Navy personnel acquired data verifying the cold-core eddy sequence (Fig. 15).

Cold-core eddies create an acoustic environment opposite to that of their warm-core counterparts. From a sound source in such an eddy, sound is projected down, eliminating, therefore, the usual surface duct.

There are severe problems, therefore, in waters where such eddies abound, and it is in eastern boundary currents where eddy sequences, pairs, and dissipating and growing boundaries occur in magnificent confusion.

In that eastern boundary currents in the waters off the west coast of the United States are characteristic, we can study them with satellite sequences to our good advantage. With two DMSP platforms in orbit, twice daily views are possible. For example, in this early morning satellite pass (Fig. 16), the computer program was set to look at the waters to the north of San Francisco. An upper level remnant of the jet stream lay across the coast, but the cold, coastal upwelling and the cold seaward plume off Cape Mendocino were clearly discernible. To the south, off San Francisco and Monterey, warm-core eddies intruded towards the coast and a long, cold front extended well to sea.

Nothing had changed in the afternoon except the jet-stream trace, but a different computer program permitted easier tracing of the cold front than was possible from the previous image.

We learn from these studies that features that at first may appear delicate and, hence, short-lived, actually remain for several days. Indeed, there are both cold and warm-eddy chains which seem indigenous to particular parts of the coast. These are clearly conditions created by the coastal and submarine topography. The

result is a quasi-permanence of eddies and fronts which change slowly in shape and intensity, and if they move, similar features are formed upstream behind them.

It is apparent that the waters of eastern boundary currents present an ASW nightmare; a nightmare that can only be ameliorated by making available to the tactical commander, the details of the real-time ocean that he needs to solve his ASW problem. And the basis of this capability is, certainly, remote sensing. So, what is to be done regarding the waters west of the English Channel?

Over and above the obvious satellite surveillance, it is essential that sophisticated, coordinated experiments be conducted similar to the concept of the Huelva Project (Fig. 17). This plan conceived by Scully-Power and myself, had all of the elements necessary to determine the hierarchy and ASW significance of the basic features in eastern boundary currents.

Although this project has yet to be conducted, the oceanographic, acoustic, and remote sensing components are those that can be easily addressed in the approaches to the English Channel.

Even though it is clear that ocean surveillance is suitably accomplished by DMSP infrared products, many boundaries readily respond in the visible spectrum, and can be seen at scales and intervals possible from manned spacecraft. It is important, therefore, that every advantage be taken of the Space Shuttle Program of the National Aeronautics and Space Administration.

An observer in orbit can make a quick visual examination of fronts and provide instantaneous details of the system when orbiting at a low (120 nm.) altitude, as Tom Stafford's observation in July 1975 pointed out so well. (Fig. 18).

That there is a certain relationship between the visual boundary and that which responds as a thermal gradient in the infrared, there can be little question--in those waters where we have coordinated data.

Of course, no matter how many examples of data we have of the sea under cloudless skies, the interminable cloudiness of the marine atmosphere makes us constantly aware of the limitations of infrared and the visible parts of the spectrum.

From some recently collected data, however, comes evidence that once a suitable microwave system can be put into orbit, the thermal boundaries for which we so eagerly search will no longer remain hidden beneath a moist, cloudy sky.

In Fig. 19, we see on the left, the infrared image of the Kuroshio Current from NOAA-5 on 10 May 1977, and on the right, the visible image scanned at the same time. (These data were reduced at the USAF DMSP site in Guam by Robert H. Whritner, Scripps *Institution of Oceanography.)*

The thermal boundaries, readily followed in the infrared image, were just as well defined in the visible image. Furthermore, it seems clear that the colder water was smoother than the warmer; a concept expressed since 1964 by American astronauts, but just recently verified by studies conducted by NASA and Navy personnel.

That such "roughness/thermal" boundaries persist under severe wind conditions is evident from an image prepared by Bob Whritner on July 12, 1977. Again, from NOAA-5, we note eddies in the waters east of Japan beneath clear skies behind an advancing front. Winds of 40 knots blew across the waters east of Hokkaido, yet the boundaries remain easily discernible in both the infrared and the visible images.

Satellite imagery has provided us information on eastern boundary currents of which we were previously unaware. Turbulence, fronts and eddy sequences were unknown in the ocean, except as a vague concept. Such turbulence in fluid flows was known in the hydraulics laboratory, however, so that we now have the opportunity to translate that experimental data and the resulting theory into the eddies and fronts in question. Furthermore, we now have the tools at hand to permit efforts to define the processes by which these turbulent waters live.

The significance of these features to the tactical ASW commander seems obvious. To attack the ASW acoustic ramifications of turbulent eastern boundary currents with those capabilities we have in hand also seems obvious.

We must recognize that the approaches to the English Channel present a problem no different, therefore, from that off Gibralter, or off San Diego. It is clear, that a tactical ASW solution for that area can be attained with a well-planned and coordinated effort. All the resources exist. It merely remains to get on with it.

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Nysen, Paul A., P. Scully-Power, and D. G. Browning, 1978. Sound Propagation Through an East Australian Current Eddy. J. Acoust. Soc. Amer, Vol 63, #5, pp. 1381-1388

Stevenson, Robert E., 1977, Huelva Front and Malaga, Spain, Eddy Chain as defined by Satellite and Oceanographic Data. Deutschen Hydrographischen Zeitschrift, Band 30, Heft 2.

FIG. 1a
Infrared image of the Atlantic Ocean off the northeast coast of the United States from NOAA-5. (Warm water is darker than the cold water in all IR images.)

FIG. 1b
Visual image of the Atlantic Ocean off the northeast coast of the United States, from NOAA-5.

FIG. 2 Infrared image of the Atlantic Ocean west of Portugal, Spain, and Morocco, 24 July 1975, from DMSP. Note, the warm eddies in the upwelling waters off Portugal, the cool tongue in the Gulf of Cadiz, the upwelling off Portugal, and the large, warm-core eddy in the Alboran Sea.

FIG. 3
Infrared image of the Pacific Ocean off northern California, Oregon, and Washington, from DMSP 06 Sept 77. The river is the Columbia, marking the boundary between the states of Washington and Oregon, and was injecting warm water into the cold upwelling waters of the coast. Note the larger tongue of cold water extending westward from Cape Mendocino, California.

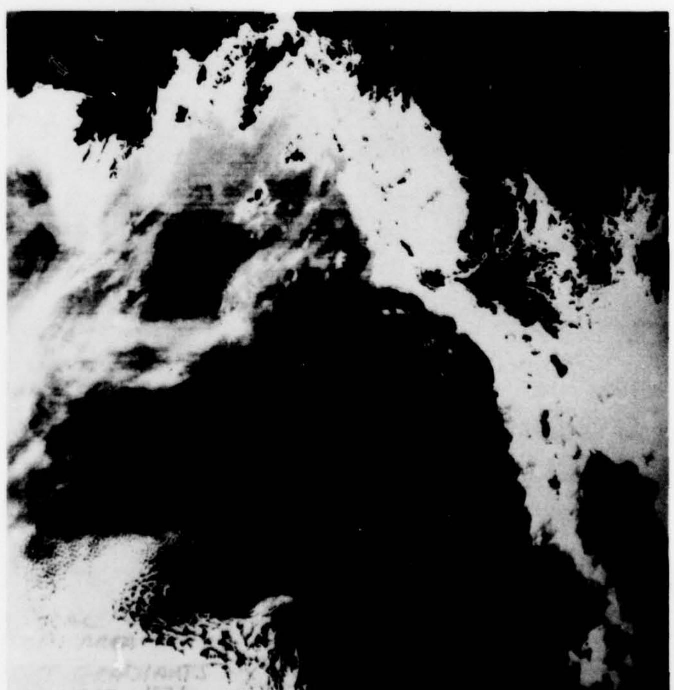


FIG. 4
Infrared image of the Pacific Ocean off southern California, 13 March 76, from DMSP. The "white" coastal lands were colder than the coldest waters, thus the "white" printout by the receiver's computer. Note the two tongues of cold, California Current water extending south, and their turbulent boundaries.

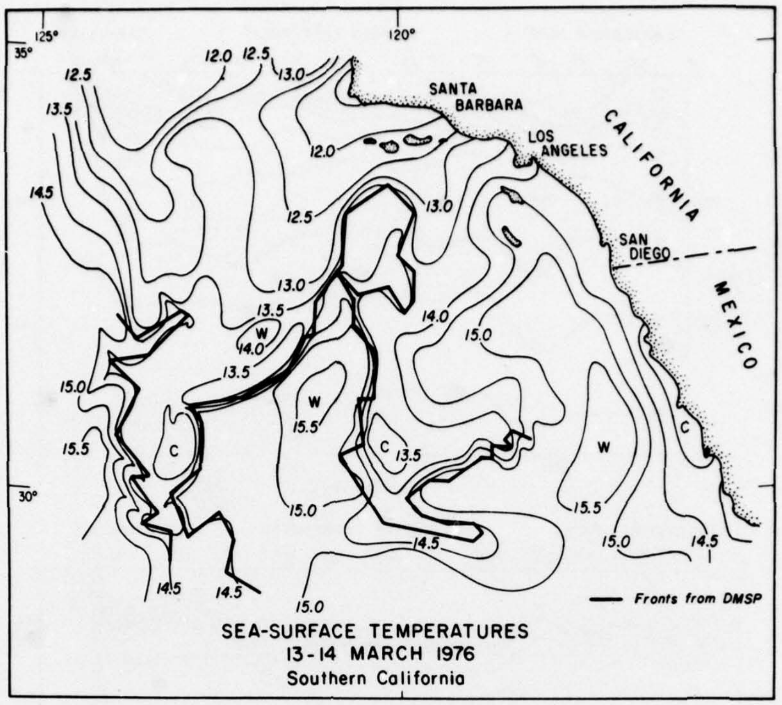


FIG. 5 Sea-surface temperatures on 13 and 14 March 77 drawn from AXBT data gathered from the RP-3 aircraft of the U.S. Naval Oceanographic Office. The heavy dark lines are sea-surface boundaries as depicted on the infrared image of Fig. 4.

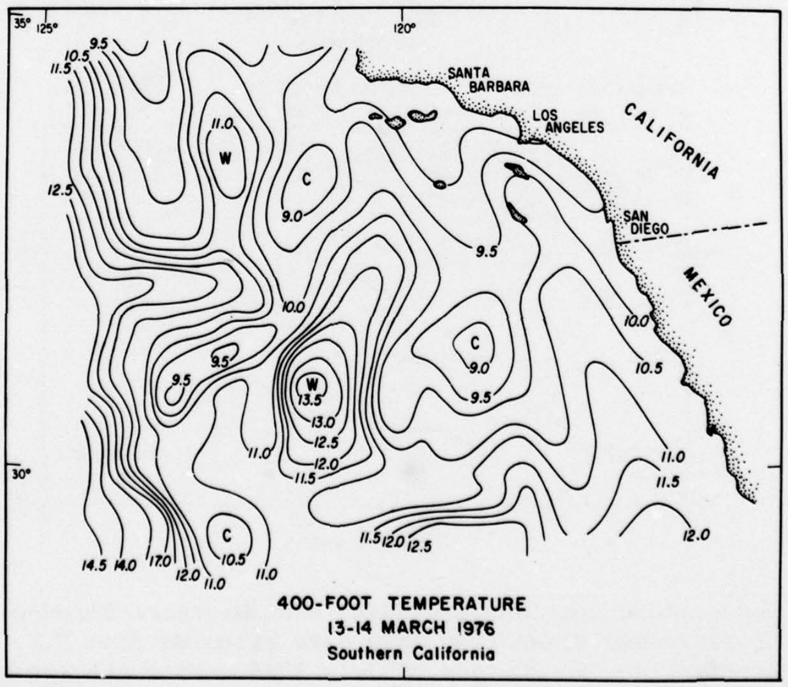


FIG. 6 Temperatures at a depth of 400 feet on 13 and 14 Mar 77 from AXBT data gathered from the RP-3 aircraft of the U.S. Naval Oceanographic Office. Note the eddies that lie beneath the tongues of warm and cold water and especially the 4°C gradient around the quasi-permanent warm-core eddu that dominates the scene.

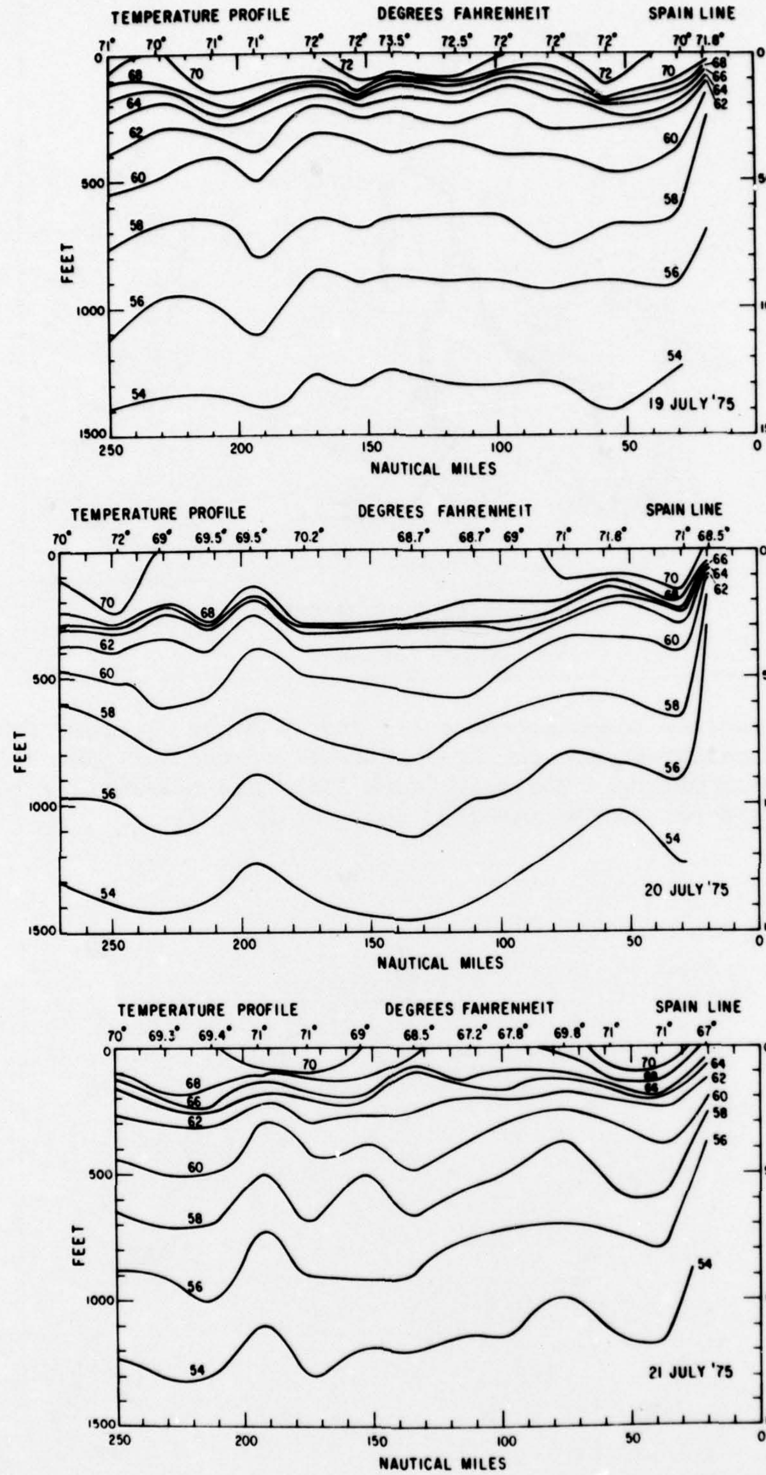


FIG. 7 Temperature sections extending southwestward through the Gulf of Cadiz and drawn from AXBT data gathered from U.S. Navy P-3 aircraft on 19, 20, and 21 July 1975. Note the rising thermocline nearby the Spanish Coast on each day, and the cold-warm-cold water sequence at 200 miles from the coast.

FIG. 8
DMSP infrared image of the Iberian Peninsula and Morocco taped aboard the USS Kennedy on 20 July 1975. The black lines on the left edge of the image indicate the edge of the IR scanner. Cold water was curving around Cabo St. Vincente with a long tongue (the Huelva Front) extending along the coast of Spain. Note the warm-core eddies in the Alboran Sea.

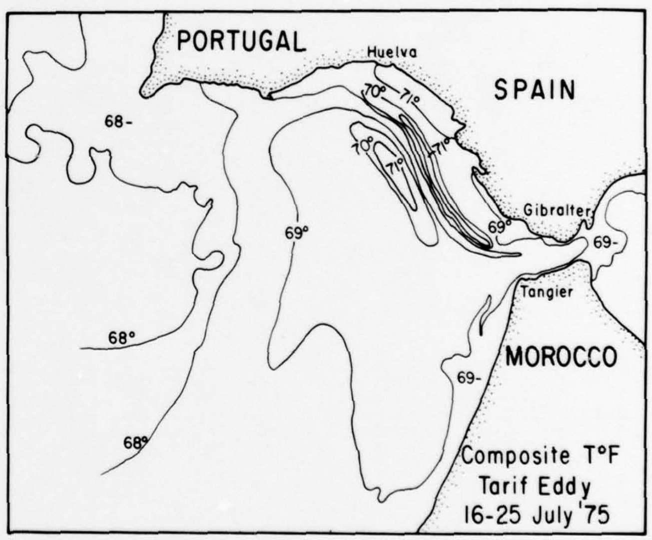


Fig. 9
Sea surface temperatures in the Atlantic Ocean west of Gibraltar drawn from data gathered from AXBT's and XBT's and the temperature gradients imaged by DMSP, 16-25 July 1975.

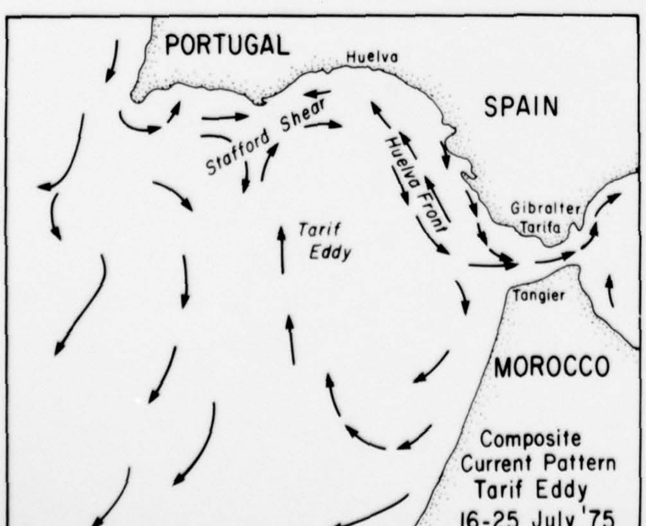


FIG. 10
Sea-surface currents in the Atlantic Ocean west of Gibraltar deduced from sea-surface temperatures and ship's tracks, 16-25 July 1975.

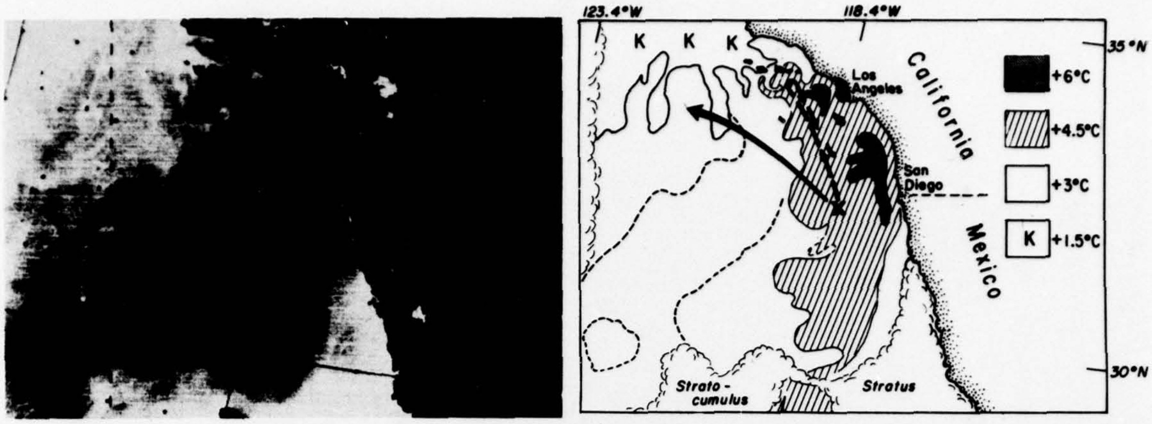


FIG. 11 DMSP infrared image of the Pacific Ocean west of southern California, 23 June 1976, along with an interpretation of the relative temperatures. The dashed line on the drawing shows the track of the USS Enterprise and the solid line the course followed by the cruiser escort on 24 June 1976 during Readiex 476.

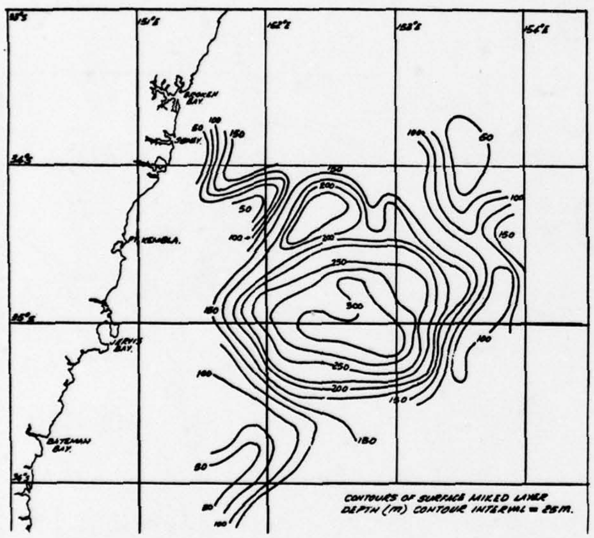
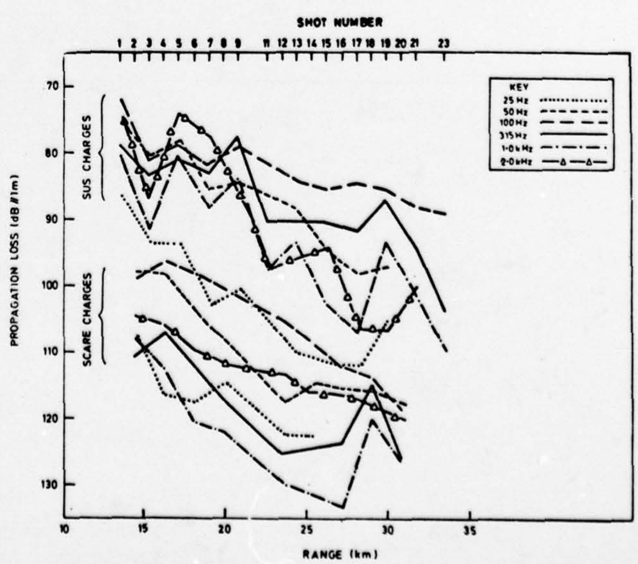


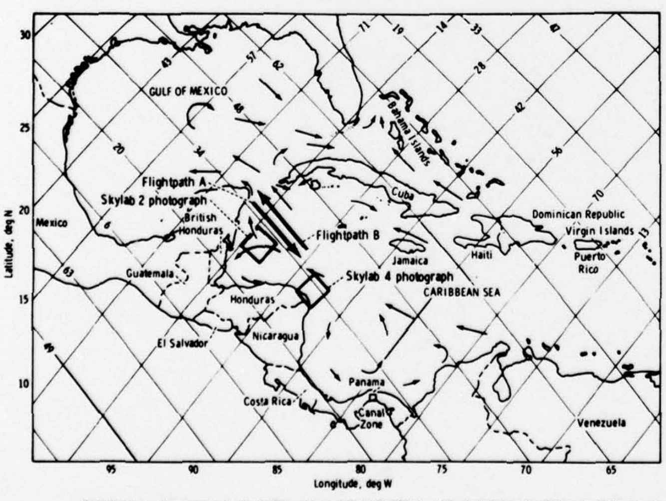
FIG. 12
Depth of the mixed layer in the ANZUS Eddy first measured in September 1974.



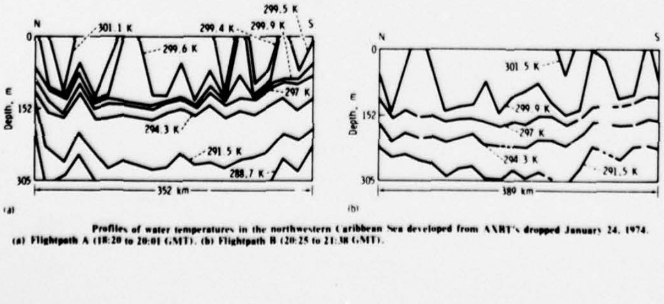
PROPAGATION LOSS VS RANGE VIA DUCT TRANSMISSION PATHS.

FIG. 13
Propagation loss versus range measured in an ANZUS Eddy in the Tasman Sea in March 1975.

FIG. 14 A black and white reproduction of a full colour vertical photograph of the northwest Caribbean Sea taken with a 6-inch lens, 70 mm format camera aboard Skylab in July 1973. The area covered is 90 n.mi by 90 n.mi and north is at the top of the picture. Trade wind, puff-ball cumulus line up with the wind direction and the sub-circular cold-core eddies are seen to disturb that pattern.



Map showing surface currents in the Caribbean Sea and the Gulf of Mexico. Also included are the flightpaths of the aircraft which dropped AXBT's. Skylab orbits are shown by numbered lines.



Profiles of water temperatures in the northwestern Caribbean Sea developed from AXBT's dropped January 24, 1974. (a) Flightpath A (18:20 to 20:01 GMT). (b) Flightpath B (20:25 to 21:38 GMT).

FIG. 15
Chart showing Skylab orbits and flight lines of the U.S. Navy P-3 aircraft on 24 Jan 1974; ocean temperature profile of the ocean under the western-most flight line (left); and ocean temperature profile under the easternmost flight line. Upward protruding cold-core eddies were more numerous to the west, on the edge of the current, than to the east in the core of the current.

FIG. 16 *DMSP infrared image of the Pacific Ocean west of northern California and southern Oregon, 7 September 1977, from data received by the Navy Weather Service Facility, North Island, California. Cirrostratus, jet-stream clouds lay over the Oregon-California border and the large, cold-water plume noted on 6 September (Fig. 3) was well defined seaward off Cape Mendocino.*

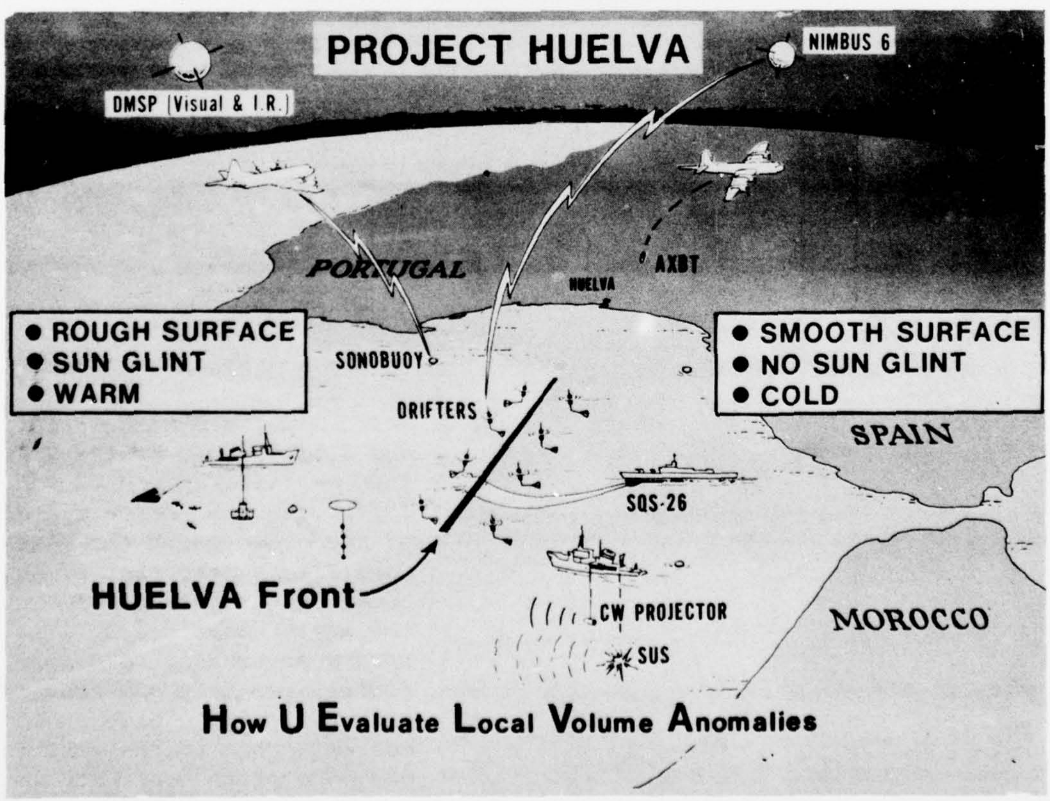


FIG. 17 *Cartoon sketch of the basic elements of Project Huelva; an ASW/oceanographic experiment planned by Robert E. Stevenson and Paul D. Scully-Power.*

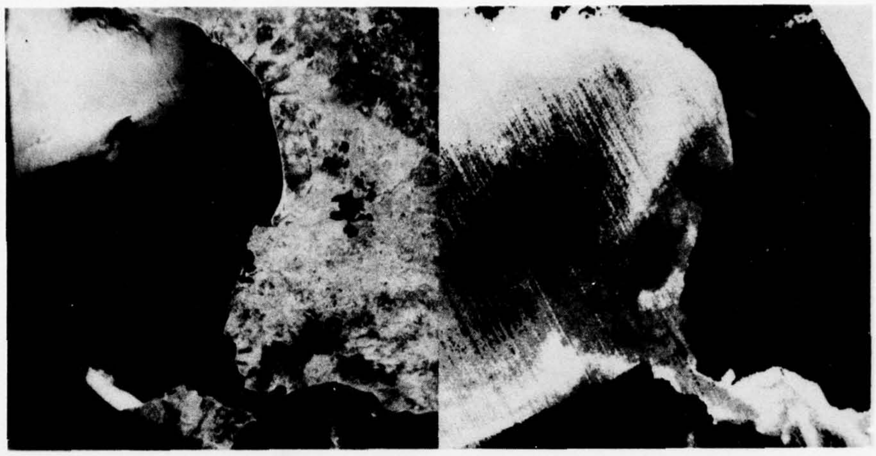


FIG. 18 Black and white reproduction of a full colour photograph of the Gulf of Cadiz taken by Lt.Gen. Thomas P. Stafford, Commander of the Apollo Spacecraft during the Apollo/Soyuz Test Project, on 20 July 1975, and an enlargement of a DMSP infrared image of the same area obtained on the same day from the receiver aboard the USS Kennedu.

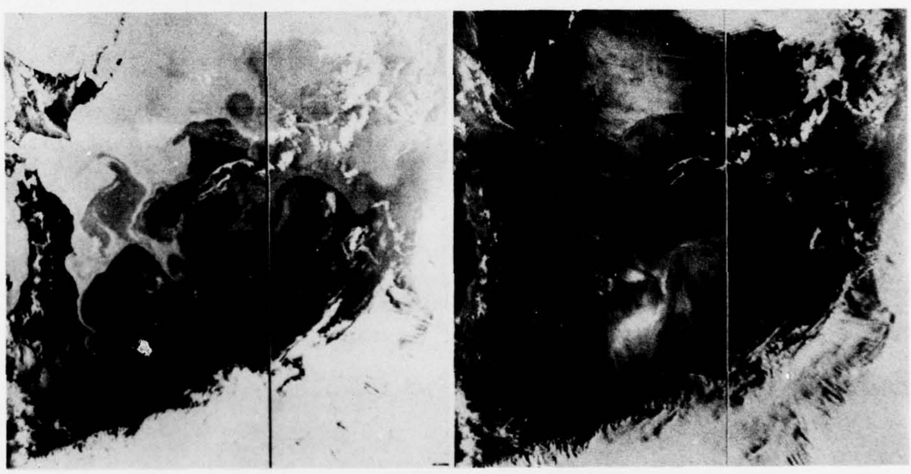


FIG. 19 Infrared image (left) and a simultaneously-acquired visible image of the Pacific Ocean east of Japan taken from the NOAA-5 satellite, 10 May 1977, and received by the USAF in Guam. The warm Kuroshio Current is easily followed in the infrared depiction, as are the cold and warm-core eddies to the north. The current and eddy boundaries were also well defined in the sun's glitter pattern, attesting to the growing knowledge that a cooler sea surface is smoother than one that has warmer temperatures.

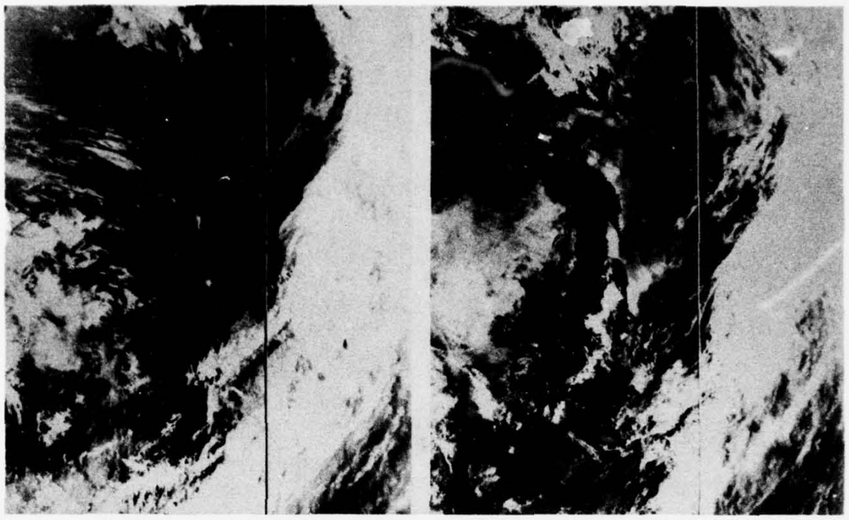


FIG. 20 Infrared image (left) and a simultaneously acquired visible image of the Pacific Ocean east of Japan taken from the NOAA-5 satellite, 12 July 1977, and received by the USAF in Guam. Note the wind streaks and the refractive wave patterns east of Hokkaido, and between Honshu and Hokkaido produced by the 40 kn westerly winds behind the front.

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